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AN OBJECTIVE METHOD FOR FORECASTING PRECIPITATION AT MONTEREY, CALIFORNIA

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AN OBJECTIVE METHOD FOR FORECASTING PRECIPITATION
AT MONTEREY, CALIFORNIA

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Henry [illegible] Jr.

AN OBJECTIVE METHOD FOR FORECASTING PRECIPITATION AT MONTEREY, CALIFORNIA

by

Henry A. Galio, Jr.

Lieutenant Junior Grade, U.S.N.R.

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
AEROLOGY

United States Naval Postgraduate School
Monterey, California

1958

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AN OBJECTIVE METHOD FOR FORECASTING PRECIPITATION AT MONTEREY, CALIFORNIA

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Henry A. Galio, Jr.

This work is accepted as fulfilling
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MASTER OF SCIENCE
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from the
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ABSTRACT

An objective method of forecasting twenty-four hour precipitation amounts at Monterey, California for the late-fall to early-spring season is presented. The system employs one 500-mb vorticity and three sea-level pressure parameters, combined subjectively by a graphical integration process. The technique is applied to forecasts of rain and no rain, with the former further specified into one of the three quantitative categories: trace - 0.15 inches, 0.16 - 0.49 inches, and ≥ 0.50 inches. Verification of the scheme is shown in the form of contingency tables, from which are computed skill scores and the percentage of correct forecasts.

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1. Introduction

Since an objective forecast system produces a unique forecast from a specific set of data, the goal of this technique is simply to eliminate as many as possible of the subjective elements which enter into its application. This type of forecast is not so much concerned with the source of hypothetical relationships as it is with the accuracy and practical value of the forecast (1).

With the above in mind, this investigation was conducted to develop an objective system of forecasting the occurrence or non-occurrence of precipitation and, in the case of the former, the actual amount, at Monterey, California.

Showalter (2), in 1944, suggested various factors that were important in quantitative precipitation forecasting, and Brier (3), in 1946, utilizing these factors, suggested the method of graphical integration for the development of an objective forecasting technique. Brier's method of graphical integration is employed in this investigation although with some modifications. Since Brier's work, there have been numerous papers on objective methods of forecasting precipitation (4-13).

2. Data

a. Times and Location

With due consideration given to the operational and military use of the proposed forecasts as well as to the availability of data, it was decided to develop a technique for forecasting precipitation for a twenty-four hour period beginning at 1020 PST at the Naval Air Facility, Monterey, utilizing sea-level and 500-mb charts and data.

The time of the pertinent maps available prior to the beginning of the forecast period is 1200Z (0400PST). However, this map time became effective after April, 1957, thus there existed insufficient 1200Z data at the beginning of this investigation. Therefore, only charts prior to April, 1957 were incorporated into the development of the objective system. The map times employed are as follows:

Sea-level	1230Z (0430PST)
500-mb	1500Z (0700PST)

The nine months: January, February, March, April, November, and December, 1956 and January, February, and March, 1957 were chosen to be the original data period. The six months, November through April, comprise the rainy season at Monterey, while during each of the other months of the year, the amounts of precipitation are less than 0.45 inches (14).

The nine months chosen contain a total of 272 cases of which 97 are rain cases. Table 1 is a breakdown of all cases into the following rainfall categories which are used throughout this study:

No Rain
T-0.15 ——— Trace to 0.15 inches
0.16-0.49 ——— 0.16 inches to 0.49
0.50- ——— 0.50 inches and greater

	Observed Precipitation (inches)				
Month, Year	No Rain	T-0.15	0.16-0.49	0.50-	
Jan., 1956	11	9	8	3	31
Feb., 1956	22	4	2	1	29
Mar., 1956	26	5			31
Apr., 1956	20	8	1	1	30
Nov., 1956	28	2			30
Dec., 1956	27	3	1		31
Jan., 1957	17	8	3	3	31
Feb., 1957	6	16	5	1	28
Mar., 1957	18	10	3		31
	175	65	23	9	272

Table I

Table of the number of cases in four observed rainfall categories as a function of selected months of the year.

b. Sources

The monthly climatological records of the Naval Air Facility, Monterey, provided twenty-four precipitation amounts and sea-level pressures. The Daily Series, Synoptic Weather Maps, Part I, Northern Hemisphere Sea-Level and 500-mb Charts, and Part II, Northern Hemisphere Data Tabulations were the sources of sea-level and 500-mb variables.

3. Graphical Integration

The technique of graphical integration as applied to forecasting precipitation involves the selection of independent variables which in some way are related to the occurrence of rain. Scatter diagrams of observed precipitation amounts are plotted as a function of two of the independent variables. Several observations are grouped into cells, at which point either of the following methods of analyses may be used:

1) For each cell, the ratio of the number of rain cases to the total number of cases is computed. This frequency value is plotted at the cell's midpoint. Finally, a probability surface is fitted to the computed frequencies by a set of isolines.

2) The arithmetic mean of each cell is computed and plotted at the cell's midpoint. Then a set of isohyets is fitted to the computed means of each cell.

In either case, the graphically-derived variable can be combined with another independent variable or with a variable which was determined by one of the above methods. This process is repeated until only one variable remains. This final variable is then a function of all the initial independent variables.

According to Thompson (13):

> The graphical technique has the disadvantage of a certain amount of subjectivity in the original combination of variables, but this is largely outweighed by its relative simplicity as well as the fact that it eliminates the necessity for having prior knowledge of, or making assumptions regarding the functional relationships between the independent variables and dependent variate, a requirement common to all mathematical regression methods. There is no lack of objectivity in the use of the charts obtained from the graphical analysis.

Brier (3), in his original study, used thirteen variables but Penn (12) only used four, while adding the complexity of a weather typing system to his technique. Thompson (13) employed six meteorological variables in his objective method. Four parameters are employed in this investigation.

4. Determination of Forecast Technique

a. Selection of Variables

As implied in Section 3, the initial problem was to select parameters which presumably are related to subsequent precipitation. The following variables were chosen considering the dynamics of the precipitation process:

1. P_{EUR} : Sea-level pressure at Eureka, California, at 1230Z (0430 PST)
2. $\zeta_8 - \zeta_M$: A variable proportional to the 500-mb geostrophic relative vorticity between Monterey and a point 8° of latitude upstream, as measured along the 500-mb contour that passes through Monterey at 1500Z (0700 PST)
3. $\Delta P_{MRY-EUR}$: Sea-level pressure difference between Monterey and Eureka at 1230Z (0430 PST)
4. $\Delta P_{MRY-LAS}$: Sea-level pressure difference between Monterey and Las Vegas, Nevada at 1230Z (0430 PST)
5. $\bar{Z}_8$: Space mean height at a point 8° of latitude upstream from Monterey, as measured along the 500-mb contour that passes through Monterey at 1500Z (0700 PST)
6. hhh_{MED} : The 500-mb height at Medford, Oregon, at 1500Z (0700 PST)
7. TT_{MED} : The 500-mb temperature at Medford at 1500Z (0700 PST)
8. $\Delta h_{MRY-MED}$: The 500-mb height difference between Monterey and Medford at 1500Z (0700 PST)
9. $\Delta T_{MRY-MED}$: The 500-mb temperature difference between Monterey and Medford at 1500Z (0700 PST)
10. ω_{500} : The 500-mb vertical velocity at Monterey at 1500Z (0700 PST)

The absence of a moisture parameter is justified by the conclusions of the committee on Quantitative Rainfall Forecasting (13) which indicates that as a rule the kinematics of cyclonic circulation (convergence and vertical motion) are much more important in determining rainfall intensity in the Monterey area than are variations in moisture.

b. Graphical Analysis

Each of these variables was plotted against precipitation to determine its relationship to the subsequent twenty-four hour rainfall.

The vertical velocity was disregarded immediately because of its current unavailability.

The first six variables yielded the best relationship with rainfall amounts. Scatter diagrams of precipitation, as a function of various combinations of these six variables, were plotted. Such combinations were:

1. P_{EUR} and $\zeta_8 - \zeta_m$
2. $\Delta P_{MRY-EUR}$ and $\Delta P_{MRY-LAS}$
3. $\zeta_8 - \zeta_m$ and $\bar{Z}_8$
4. $\Delta P_{MRY-EUR}$ and $\zeta_8 - \zeta_m$
5. $\Delta P_{MRY-EUR}$ and hhh_{MED}
6. P_{EUR} and $\Delta P_{MRY-LAS}$

Each of the above graphs was analyzed in the manner described by method two in Section 3, with the following exception: the zero line was drawn as the best separation between rain and no rain cases.

After careful inspection of all six graphs, two (Figures 1 and 2) were selected because these analyzed graphs indicated the best separation between rain and no rain cases and the isohyets were regular and yielded a reasonable and explainable pattern.

The lack of a sufficient number of observations greater than 0.50 inch (only 9 out of 97 or approximately 9%) is the reason for the abrupt termination of the analysis with the 0.50 inch isohyet. The use of more months of data would remedy this situation, although twenty-four hour precipitation amounts greater than 0.50 inch are not a common occurrence at Monterey (15).

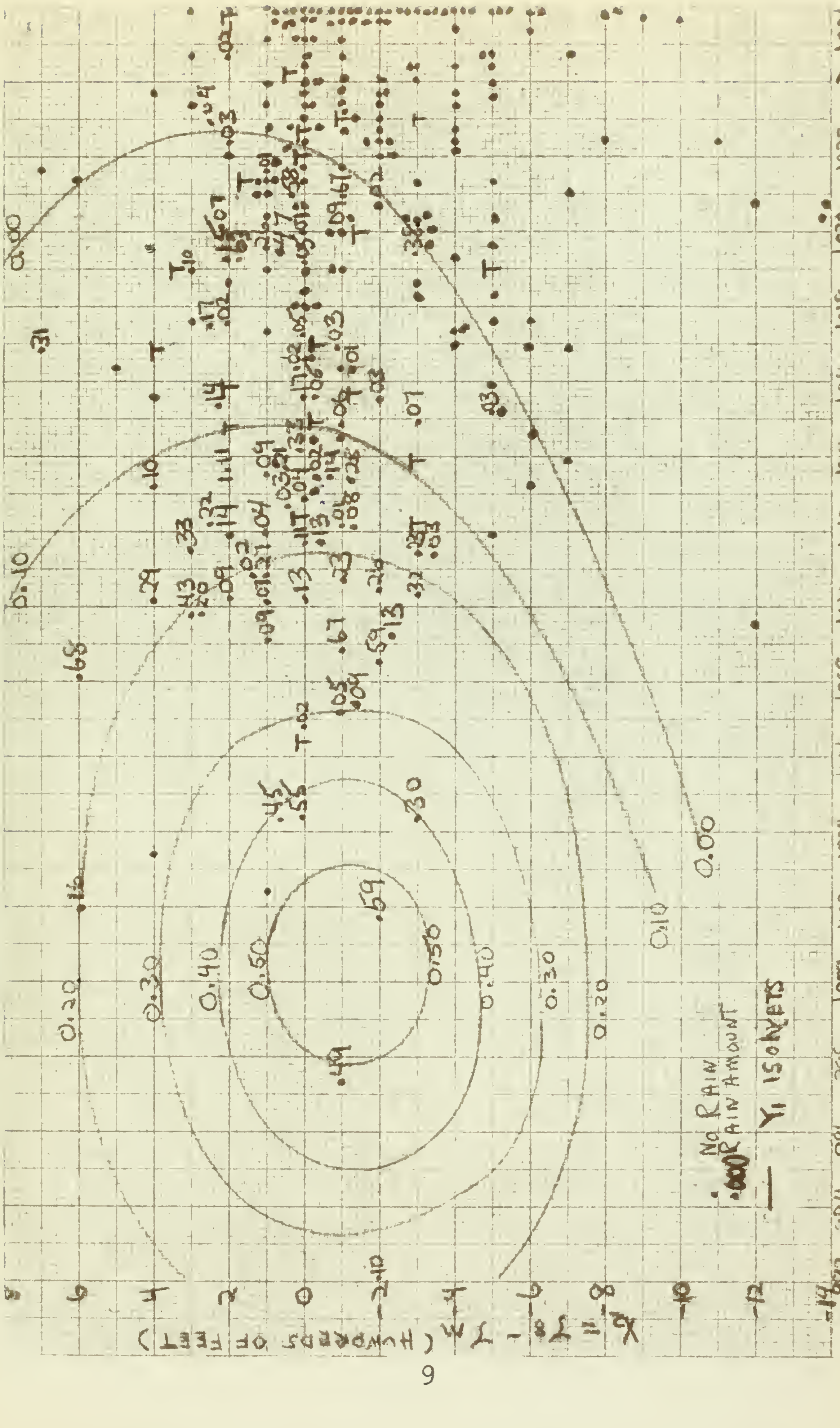


Figure 1- Scatter diagram of precipitation as a function of P_{EUR} and $Z_8 - Z_m$ with isohyets (Y_1)

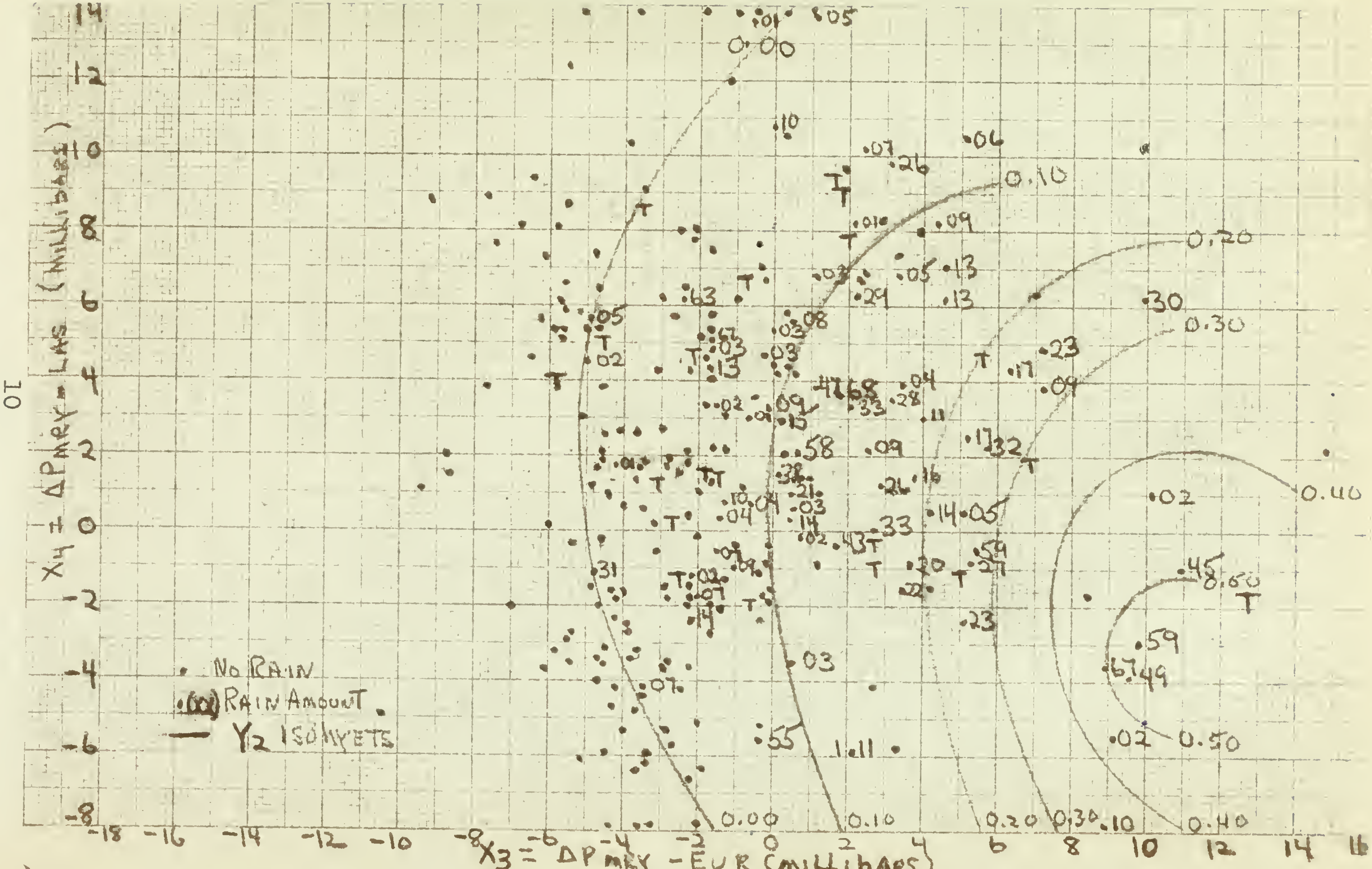


Figure 2- Scatter diagram of precipitation as a function of $\Delta P_{MRY-EUR}$ and $\Delta P_{MRY-LAS}$ with isohyets (Y_2)

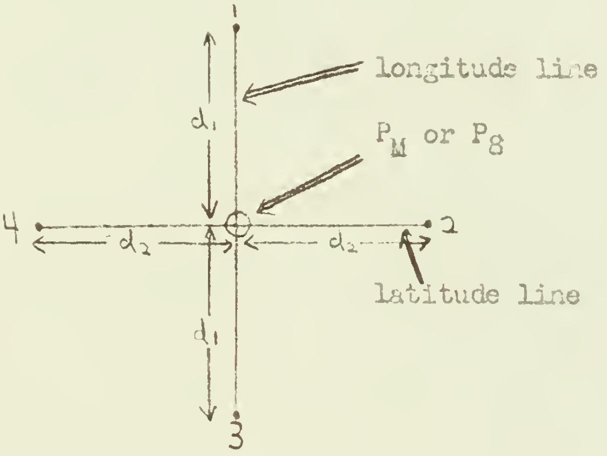
c. Relationship of Selected Variables to Precipitation.

The relationship of the selected variables to precipitation, as determined from Figures 1 and 2, are as follows:

$P_{EUK} = X_1$: The sea-level pressure at Eureka is a measure of the central pressure (and hence intensity) of the storm system affecting Monterey, since the normal storm track for the months included in this study is in the vicinity of Eureka (16). Eureka's sea-level pressure varies indirectly with Monterey's precipitation for pressures greater than 1000 mbs, quite reasonably indicating definite cyclonic flow with larger values of rainfall. However, it is to be noted that for pressures lower than 1000 mbs the precipitation varies directly with pressure. At these low pressures the local area is likely to be ahead of, at, or just behind the center of the system. Thus, these three areas, taken together, do not specify a particular relationship with precipitation.

$\zeta_8 - \zeta_M = X_2$: The variables ζ_8 and ζ_M can be considered proportional to the 500-mb geostrophic relative vorticity and have been determined in the manner explained in (17, 18). Thus, the geostrophic relative vorticity: $\zeta_g = g/fd^2 \ (Z_1 + Z_2 + Z_3 + Z_4 - 4Z_0)$. Considering g/fd^2 as a constant, (K), ζ_g is proportional to $(Z_1 + Z_2 + Z_3 + Z_4 - 4Z_0)$.

Utilizing this relationship for the particular application at hand, ζ_M is equal to ζ_g/K. Hence, ζ_M is equivalent to the sum of 500-mb heights: Z_1, Z_2, Z_3, and Z_4 at distances: d_1, d_2, d_3, and d_4, respectively, from Monterey, minus four times the 500-mb height at Monterey: $4Z_0$. A similar operation determines ζ_8 for a point 8° of latitude upstream from Monterey. The following sketch exemplifies the grid used in this calculation:



where d_1 = [illegible]° latitude

d_2 = [illegible]° longitude

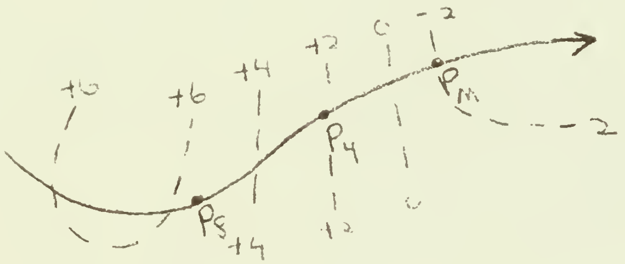
P_M = Monterey

and P_8 = point 8° latitude upstream from Monterey

The significance of ζ_8 and ζ_M lie in the manner in which they are measured. The algebraic sign of the variable $(\zeta_8 - \zeta_M)$ can be considered as representative of the algebraic sign of the 500-mb advection of geostrophic relative vorticity at a point half way distant between Monterey and the location 8° latitude upstream. Of course, this will be true, in general, only if the advection of vorticity along the contour between P_8 and P_M does not change algebraic sign. The two following examples show typical situations schematically:

Example 1:

Algebraic sign of $\zeta_8 - \zeta_M$ is representative of the advection at a point halfway between P_M and P_8.



legend:

——— = 500-mb contour through Monterey

– – – = isoline of $\zeta_{g/h}$ in hundreds of feet

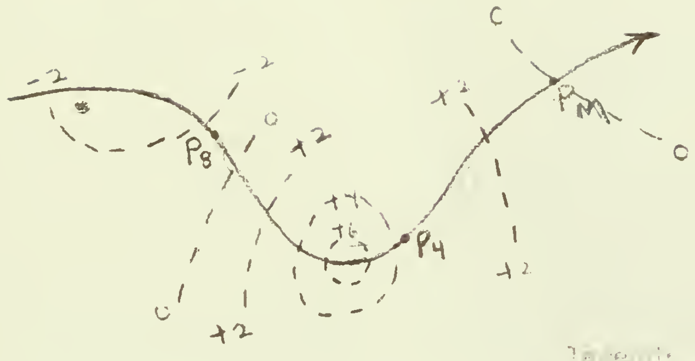
P_M = Monterey

P_8 = point 8° latitude upstream from Monterey

P_4 = point 4° latitude upstream from Monterey

Example 2:

Consideration of $\zeta_4 - \zeta_8$ as representative of the advection of a point halfway between P_4 and P_8.



Legend: as in Example 1.

Now, from the approximate relationship that exists between vorticity advection and horizontal velocity divergence (17), $\left(\underline{\nabla}_p \cdot \underline{V} \approx -\frac{1}{\zeta_a} \underline{V} \cdot \underline{\nabla} \zeta\right)$, as well as from observations (19), 500-mb positive advection is associated with 500-mb divergence, sea-level pressure falls, clouds, and precipitation, and 500-mb negative advection is associated with 500-mb convergence, sea-level pressure rises, and good weather.

For Example 1, assuming that the 8° latitude contour interval chosen is reasonable,* one expects the advection occurring at P_4 at forecast time to move over Monterey sometime in the middle of the twenty-four hour forecast period. Thus, a positive $\zeta_8 - \zeta_M$ should be associated with subsequent precipitation at Monterey. However, Figure 1 indicates that the largest values of precipitation are associated with slightly negative values of $\zeta_8 - \zeta_M$, suggesting that the usual wintertime situation near Monterey is depicted by Example 2, above, rather than by Example 1.

---

*Short-wave troughs and their associated features move with an average winter speed of 22 kts (20).

$\Delta P_{MRY-EUR} = X_3$: This is the sea-level pressure difference between Monterey and Eureka, and is a measure of the southwest-northeast component of the geostrophic wind.

According to Showalter (2), the sea-level pressure gradients are a measure of inflow into a low pressure system and hence the low-level convergence associated with the system.

Precipitation amounts vary directly with positive values of $\Delta P_{MRY-EUR}$, with the larger values of the parameter indicating very well the low-level convergence accompanying strong moist southwest flow.

$\Delta P_{MRY-LAS} = X_4$: This is the sea-level pressure difference between Monterey and Las Vegas. It is a measure of the north-south component of the geostrophic wind, and indicates associated low-level convergence.

Since storms approach the coast from the west, negative values of this variable ought to be associated with maximum rainfall amounts. However, it is reasonable to expect that these values will be only slightly negative since large negative values (i.e. large pressure difference between Monterey and Las Vegas) are likely to be experienced in connection with strong southerly winds east of Monterey, even prior to the forecast period. When large negative values of the parameter occur, the rain-producing section of the storm has, very likely, passed Monterey.

Figure 1, which is a scatter diagram of observed precipitation amounts plotted as a function of P_{EUR} and $\zeta_8 - \zeta_m$ with isopleths of I_1, shows that the maximum-valued isopleth occurs with low values of sea-level pressure at Eureka and with slightly negative values of the vorticity parameter. With sea-level pressures of [illegible] mbs and lower, the upper air trough is likely to be in close proximity of

Monterey, and hence Example 2 for the $\zeta_8 - \zeta_M$ parameter applies. It is reasonable to expect appreciable rainfall just in advance of the 500-mb trough passage. Further, the figure indicates that as the values of P_{Eur} increase, $\zeta_8 - \zeta_M$ becomes more positive for maximum precipitation amounts.

Figure 2, which is a scatter diagram of observed precipitation amounts plotted as a function of $\Delta P_{MRY-EUR}$ and $\Delta P_{MRY-LAS}$ with isohyets of Y_2, shows that the maximum value of the isopleths is associated with large positive values of $\Delta P_{MRY-EUR}$ and slightly negative values of $\Delta P_{MRY-LAS}$.

As the values of $\Delta P_{MRY-EUR}$ algebraically decrease, $\Delta P_{MRY-LAS}$ becomes more positive for maximum precipitation amounts.

d. Preparation of Final Forecast Graph

Figure 3 was prepared similar to Figures 1 and 2, using the variables Y_1 and Y_2 as derived from the two latter figures. However, only that data yielding isohyet values of Y_1 and $Y_2 \geqslant 0$ were used as a basis for the construction of the Y_3 isohyets in Figure 3.

From the Y_3 values obtained for each observation plotted in Figure 3, a contingency table (Table 2) of six classes of Y_3 and four categories of observed precipitation was prepared.

Table 3, which shows the cumulative frequencies and per cent occurrences of the various precipitation categories as a function of classes of Y_3, was prepared using the data of Table 2. The cumulative frequencies obtained in Table 3 were then plotted against the midpoints of the various Y_3 intervals. Following this, the data were analyzed in order to separate the four precipitation categories as shown in Figure 4.

Next, for each value of Y_3 (from Figure [illegible]) the probability of each of the four precipitation categories was tabulated in Table 6. As a function of Y_3 values, the following most probable forecasts apply:

Y_3	Most Probable Forecast
0.00 - 0.04	No rain
0.05 - 0.20	Trace - 0.10 inches
0.21 - 0.48	0.11 - 0.50 inches
0.49 and greater	0.51 inches and greater

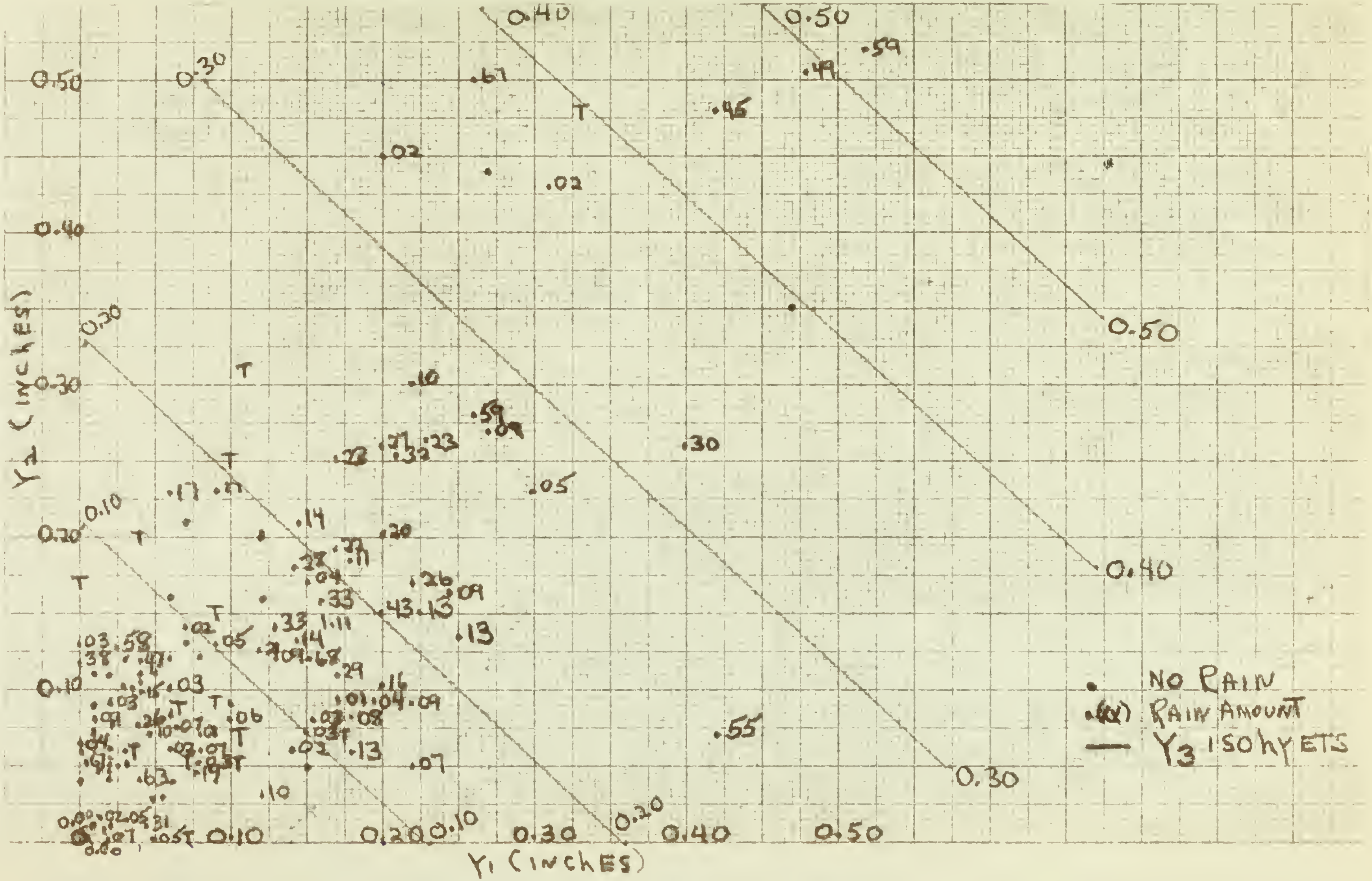


Figure 3- Scatter diagram of precipitation as a function of Y_1 and Y_2 with isohyets(Y_3)

		Y_3 (inches)						
		0.01-0.10	0.11-0.20	0.21-0.30	0.31-0.40	0.41-0.50	0.51-	
Observed Precipitation (inches)	No Rain	36	3		2			41
	T-0.15	31	13	10	3			57
	0.16-0.49	5	7	8	2	1		23
	0.50-	3	2	3			1	9
		75	25	21	7	1	1	130

Table 2

Table of the number of cases in four observed rainfall categories as a function of six classes of Y_3.

		Y_3 (inches)					
		0.01-0.10	0.11-0.20	0.21-0.30	0.31-0.40	0.41-0.50	0.51-
Observed Precipitation (inches)	0 - No Rain	36 48%	3 12%	0 0%	2 29%	0 0%	0 0%
	1 - ≤ 0.15	67 89%	16 64%	10 48%	5 71%	0 0%	0 0%
	2 - ≤ 0.49	72 96%	23 92%	18 86%	7 100%	1 100%	0 0%
	3 - ≤ 0.50 and greater	75 100%	25 100%	21 100%	7 100%	1 100%	1 100%

Table 3

Table of the cumulative frequencies of four observed rainfall categories as a function of six classes of Y_3.

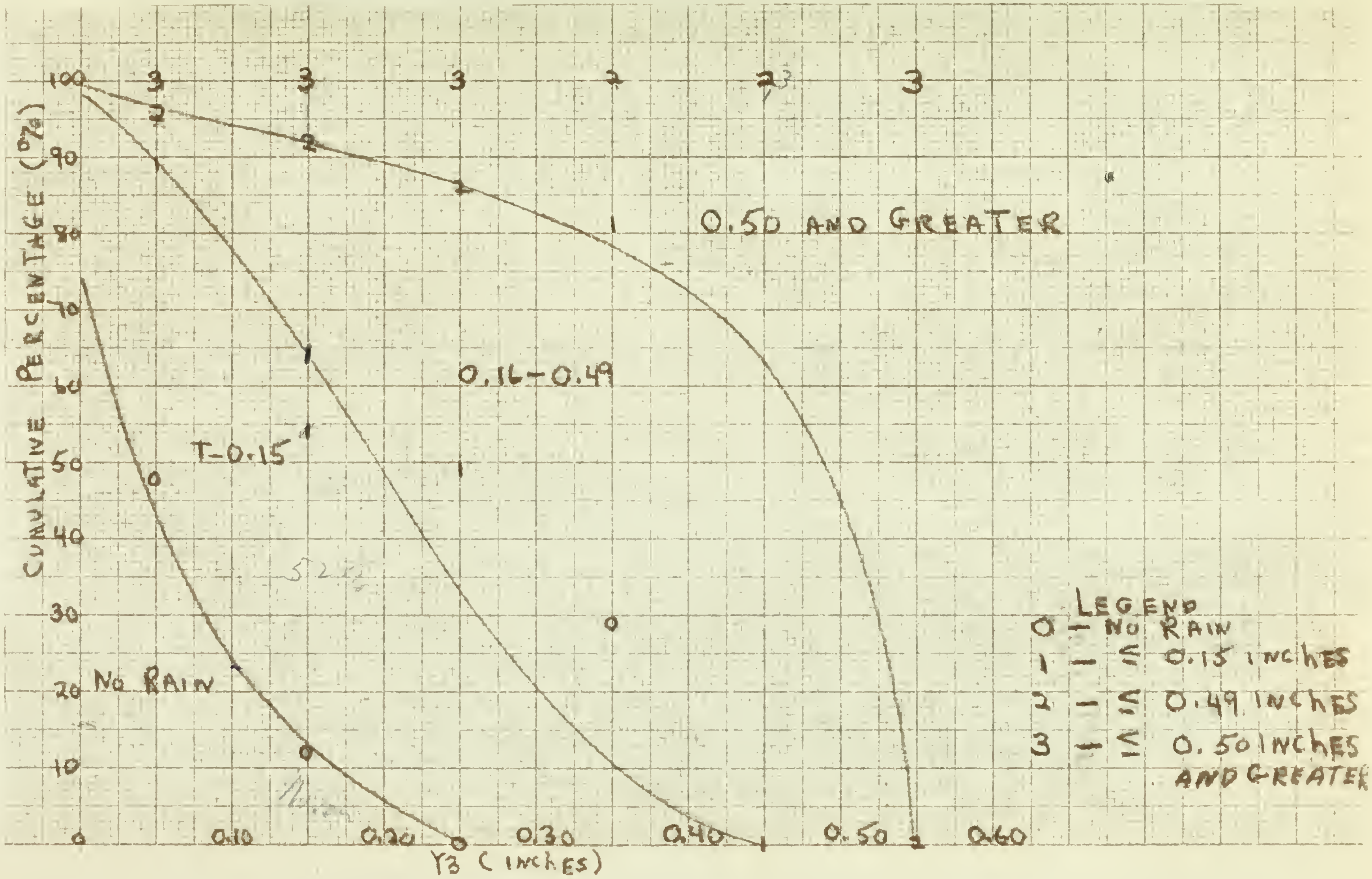


Figure 4- Cumulative percentage frequency of selected rainfall-amount categories as a function of Y_3

		Observed Precipitation (inches)			
		No Rain	T-0.15	0.16 - 0.49	0.50-
Y_3 (inches)	0.00	74	24	1	1
	0.01	68	23	3	1
	0.02	61	34	3	2
	0.03	54	39	4	3
	0.04	49	42	6	3
	0.05	44	45	7	4
	0.06	39	48	8	5
	0.07	35	49	11	5
	0.08	31	51	13	5
	0.09	28	52	14	6
	0.10	25	52	17	6
	0.11	22	53	18	7
	0.12	19	53	21	7
	0.13	17	52	24	7
	0.14	14	52	26	8
	0.15	12	52	28	8
	0.16	10	51	30	9
	0.17	9	48	34	9
	0.18	8	47	35	10
	0.19	6	46	38	10
	0.20	5	43	41	11
	0.21	4	41	44	11
	0.22	3	39	44	12
	0.23	2	37	48	13
	0.24	1	35	51	13
	0.25	0	33	53	14

Table 4

	Observed Precipitation (inches)			
	No Rain	T-.1[illegible]	[illegible]	[illegible]
0.26		30	56	14
0.27		22	57	15
0.28		25	59	16
0.29		23	60	17
0.30		20	62	18
0.31		18	63	19
0.32		16	65	19
0.33		14	66	20
0.34		12	67	21
0.35		11	67	22
0.36		9	68	23
Y_3 (inches) 0.37		8	68	24
0.38		7	68	25
0.39		5	68	27
0.40		3	69	28
0.41		3	67	30
0.42		2	67	31
0.43		1	66	33
0.44		0	65	35
0.45			63	37
0.46			60	40
0.47			57	43
0.48			53	47
0.49			49	51
0.50			44	56

Table 4

Table of probability of four observed rainfall categories as a function of Y_3.

e. Forecast Procedure

(1) Enter Figure 1 with X_1 and X_2, obtaining a value for Y_1. If Y_1 is less than zero, forecast no rain. However, if Y_1 is equal to or greater than zero record this value and proceed to Figure 2.

(2) Enter Figure 2 with X_3 and X_4, obtaining a value for Y_2. If Y_2 is less than zero, forecast no rain. However, if Y_2 is equal to or greater than zero record this value and proceed to Figure 3.

(3) Enter Figure 3 with Y_1 and Y_2, obtaining a value for Y_3. Then, enter Table 4 with the latter value to obtain the forecast probability of each of the four categories of rainfall.

f. Examples

Case I
November 15, 1954

$X_1 = 998.3$ mbs

$X_2 = +3.0$ hundreds of feet

$X_3 = +8.0$ mbs

$X_4 = -3.[illegible]$ mbs

$Y_1 = 24$

$Y_2 = 35$

$Y_3 = [illegible]$

Forecast Category (inches)	Probability (%)
No Rain	0
Trace - 0.15	12
0.15 - 0.49	67
0.50 and greater	21

Forecast: 0.15 - 0.49 inches

Observed: 0.[illegible] inches

Case II:

November 27, 1954

$X_1 = 1028.8$ mbs

$X_2 = 3.0$ hundreds of feet

$Y_1 < 0$

Forecast: No Rain

Observed: No Rain

5. Results

a. Verification of Original Data

As a quantitative measure of the accuracy of the objective forecasting system, the original data were verified and the results are presented in Tables 5 and 6.

The forecasts were verified according to:

1. The percentage of correct forecasts, defined as the ratio of the number of correct forecasts to the total number of forecasts.

2. Skill score (21), where

$$\text{Skill Score} = \frac{C - E}{T - E}$$

C = correct number of forecasts

T = total number of forecasts

E = number of forecasts expected to be correct due to chance, persistence or climatology. Chance was used as the basis for all skill scores computed in this investigation.*

The skill score can be interpreted as the percentage of correct forecasts over and above the number expected to be correct due to chance alone. The skill score is zero if the number correct is equal to the number expected to be correct, and is equal to one for perfect forecasting. A negative skill score is possible if the number correct is less than the number expected to be correct.

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*It was determined that chance would have yielded a greater number of correct forecasts than persistence, and therefore had persistence been used as the basis of the number expected to be correct, all skill scores would improve.

Table 5 is the contingency table showing the verification of the objective forecasts, using four precipitation categories, for the original data. The percentage of correct forecasts is 72 and the skill score is 0.50.

Table 6 is the contingency table showing verification of the objective forecasts, using only the rain or no-rain categories, for the original data. The forecasts are correct 85 per cent of the time, with a skill score of 0.67.

b. Independent Test Data

(1) Group I

Three months (November and December, 1954 and April, 1957) were chosen as independent test data. These are months which had the same map times as the original data. The objective technique developed earlier was applied and Tables 7 and 8 are the results.

In comparing the original data (Table 5) with the independent test data (Table 7), with respect to the four quantitative precipitation categories, the results are similar:

	Original Data	Independent Test Data Group I
Per Cent Correct	74	[illegible]
Skill Score	0.50	[illegible]

A comparison of the original data (Table 6) with the independent test data (Table 8), with respect to the rain and no-rain categories, yields the following similar results:

	Original Data	Independent Test Data Group I
Per Cent Correct	85	85
Skill Score	0.67	0.65

Independent Test Data

(2) Group II

Since April, 1957, the times of both the sea-level and 500-mb maps have been 1200Z (0400 PST) as compared to the map times for the original data. In order to ascertain the feasibility of application of this objective technique to current maps, the months of February and March, 1958 were chosen as a second set of independent test data. Contingency Tables 9 and 10 are the results.

The comparison of Table 9 to Tables 5 and 7, for the four categorical forecasts, shows the following:

	Original Data	Independent Test Data Group I	Independent Test Data Group II
Per Cent Correct	74	71	51
Skill Score	0.50	0.42	0.21

From the above, one notes the relatively low values, both in per cent correct and skill score, of the current independent test data. These lower values can be attributed partly to the three hour difference in the vorticity variable, and partly to the fact that the particular months chosen were very anomalous in the percentage of days with rain.

However, comparing the results of the rain and no-rain forecasts, (Tables 6, 8, and 10), the three verifications are more homogeneous with respect to the per cent correct and skill score, as indicated below:

	Original Data	Independent Test Data Group I	Independent Test Data Group II
Per Cent Correct	85	85	[illegible]
Skill Score	0.67	[illegible]	[illegible]

		Observed Precipitation (inches)				
		No Rain	T-0.15	0.16-0.49	0.50-	
	No Rain	152	21	2		175
Forecast	T-0.15	15	38	12		65
Precipitation (inches)	0.16-0.49	1	11	10	1	23
	0.50-	2	3	3	1	9
		170	73	27	2	272

Per Cent Correct: $\frac{201}{272} = 74\%$

Skill Score: $\frac{201-129}{272-129} = 0.50$

Table 5

Contingency table showing verification of objective forecasts (four categories) for original data (Jan. through Apr., Nov., Dec., 1956, Jan. through Mar., 1957).

		Observed		
		No Rain	Rain	
Forecast	No Rain	152	23	175
	Rain	18	79	97
		170	102	272

Per Cent Correct: $\frac{231}{272} = 85\%$

Skill Score: $\frac{231-146}{272-146} = 0.67$

Table 6

Contingency table showing verification of objective forecasts (rain and no rain) for original data (Jan. through Apr., Nov., Dec., 1956, Jan. through Mar., 1957).

		Observed Precipitation (inches)				
		No Rain	T-0.15	0.16-0.49	0.50-	
Forecast	No Rain	54	9			63
Precipitation (inches)	T-0.15	5	8	3		16
	0.16-0.49		5	3		8
	0.50		2	2		4
		59	24	8		91

Per Cent Correct: $\frac{65}{91} = 71\%$

Skill Score: $\frac{65-46}{91-46} = 0.42$

Table 7

Contingency table showing verification of objective forecasts (four categories) for independent test data (Nov. and Dec., 1954, Apr., 1957).

		Observed		
		No Rain	Rain	
Forecast	No Rain	54	9	63
	Rain	5	23	28
		59	32	91

Per Cent Correct: $\frac{77}{91} = 85\%$

Skill Score $\frac{77-51}{91-51} = 0.$[illegible]

Table 8

Contingency table showing verification of objective forecasts (rain and no rain) for independent test data (Nov. and Dec., 1954, Apr., 1957).

		Observed Precipitation (inches)				
		No Rain	T-0.15	0.16-0.49	0.50-	
Forecast Precipitation (inches)	No Rain	10	5	3		18
	T-0.15	3	13	8		24
	0.16-0.49		3	3		6
	0.50-		3	2	2	7
		13	24	16	2	55

Per Cent Correct: $\frac{28}{51} = 51\%$

Skill Score $\frac{28-17}{55-17} = 0.24$

Table 9

Contingency table showing verification of objective forecasts (four categories) for independent test data (Feb. and Mar., 1958).

		Observed		
		No Rain	Rain	
Forecast	No Rain	10	8	18
	Rain	3	34	37
		13	42	55

Per Cent Correct: $\frac{44}{55} = 80\%$

Skill Score: $\frac{44-33}{55-33} = 0.50$

Table 10

Contingency table showing verification of objective forecasts (rain and no rain) for independent test data (Feb. and Mar., 1958).

6. Conclusions

As the results clearly indicate, the separation between rain and no-rain cases can be considered as good as or better than subjective methods. Besides being correct approximately 85 per cent of the time, there is a considerable amount of skill involved.

Moreover, if rain is forecast, the probability for the occurrence of a given amount of precipitation can be obtained. Even though the results of the verifications of the four precipitation categories are somewhat less than the rain or no-rain forecasts, a rainfall-amount forecast is important for industrial, agricultural, and military operations.

It is apparent that in forecasting larger precipitation amounts (i.e., greater than 0.50 inches), this system needs improvement. However, preliminary attempts to remedy this situation failed. The final variable, Y_3, was plotted against observed precipitation with intentions of fitting a regression line to correct for the under-prediction of large rainfall amounts. This failed because of the wide scatter of points. The recommendations a, b, and e in the following section indicate possible ways to achieve the desired improvement.

A measure of the professional acceptability of the indicated results should be its relative comparison to similar operational techniques used in other localities. For this comparison, the reader is referred to (13).

7. Recommendations for Future Research

The following are suggestions, which could not be pursued in this investigation because of time limitations:

a. The number of variables incorporated in this objective system should be increased to enhance the forecasting accuracy. It is believed that a low-troposphere temperature parameter, as a measure of air-mass stability, would give better results in forecasting the rainfall category $>$ 0.50 inches. Also, a measure of the locality's proximity to the jet axis might increase the accuracy of the objective method. In fact, a number of parameters, well-correlated with precipitation, could be included in this system.

b. The amount of original data should be increased and this, too, would probably lead to better results in the largest rainfall category.

c. An investigation should be carried out to determine the effects of applying current (i.e. 1200Z) maps to the objective method. In particular, the fact that the vorticity difference on current maps is taken three hours earlier than that for the original data may have a significant effect on the results.

d. As an alternative to c. above, this objective method could be redeveloped with current observations when sufficient data is available.

e. The verifications of the months of February and March, 1958 suggest the extreme departure of rainfall from normalcy as a possible correction factor to increase the forecast accuracy of the largest precipitation category. This may be checked further as adequate records are now becoming available for this locality.*

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*The Aerology Department, U. S. Naval Postgraduate School, is currently conducting a program of collecting daily rainfall data from a number of local observation points manned by volunteer observers.

f. An area-averaged precipitation amount would be of considerable importance since a recent study (15) has indicated that rainfall at the Naval Air Facility, Monterey, is 15% below the average for the Monterey Peninsula.

g. The forecast period should be extended eventually to cover a 36- and possibly a 48-hour period.

8. Acknowledgements

The author wishes to express his appreciation for the assistance and encouragement given him in this investigation by Assistant Professor Robert J. Renard, Aerology Department, U. S. Naval Postgraduate School. The Naval Air Facility, Monterey and the U. S. Weather Bureau Stations, Eureka, California and Las Vegas, Nevada are thanked for their kind cooperation in supplying data.

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